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Abstract

As identified by the detailed long-term monitoring networks at Plynlimon, increased sediment supply to upland fluvial systems is often associated with forestry land-use and practice. Literature is reviewed, in the light of recent results from Plynlimon sediment studies, to enable identification of the potential ecological impacts of fluvial particulate inputs to upland gravel bed rivers draining forested catchments similar to the headwaters of the River Severn. Both sediment transport and deposition can have significant impacts upon aquatic vertebrates, invertebrates and plants.

Introduction

Enhanced sediment delivery to fluvial systems has been associated with all stages of the forest rotation (Newson and Leeks, 1987; Soutar, 1989; Leeks, 1992). Although this can include both fine and coarse material, the majority of research on physical sediment pollution has been undertaken on the impacts of fine material outputs, which therefore forms the bulk of this review. It should be added that changes in coarse sediment inputs, as observed at Plynlimon, can cause channel instability, resulting in geomorphological change which may affect the community within this habitat.

Anthropological impacts of fluvial sediment include the effect of increased turbidity in reducing the aesthetic quality and therefore recreational value of watercourses (Robinson, 1973), and impacts upon potable water resources due to increased treatment costs or damage to distribution systems (Marks, 1994). Fluvial sediment inputs can also lead to accelerated deposition within downstream storage areas (Duck, 1985), which may affect reservoir operations. As sediment can carry chemical pollutants such as nutrients, heavy metals and agrochemicals, and biological contaminants such as bacteria and viruses, it can also be indirectly responsible for both chemical and biological pollution (Robinson, 1973).

Although both are related to fluvial particulate inputs, different ecological impacts are associated with suspended sediment and sediment deposition. The impacts of each are therefore described for fish, invertebrates and plants.

Impacts of Fluvial Sediment Inputs on Salmonid Fish

Most research on fluvial sediment impacts upon freshwater biota has been directed towards salmonid fish species, which are common within European and North American upland watercourses. These include salmon and trout which are of economic importance through both commercial and sport fishing. Although salmonids are known to be particularly susceptible to sediment pollution, similar impacts may affect species belonging to other families, but have not been extensively recorded in the literature.

Many of the reported impacts of fluvial sediment inputs on salmonids are specifically associated with forestry. For example, in an investigation of forestry impacts upon water quality in Idaho U.S.A., over a quarter of the operations studied by Bauer (1985) were found to represent a major hazard to salmonid habitats.

For the purposes of this review, the impacts of fluvial sediment inputs on salmonid fish have been separated into the effects upon reproductive success and post-emergence survival. These impacts correspond approximately to the effects of sediment deposition and suspended sediment transport respectively.

REPRODUCTIVE SUCCESS

The most significant impact of fluvial sediment inputs on salmonid populations is reduced reproductive success due to fine sediment deposition within spawning gravel. This can result in severely depleted salmonid populations in reaches where habitat and general water quality are capable of supporting juvenile fish (Wightman, 1987; Naismith *et al.*, 1996).

Bed material within British upland gravel-bed watercourses commonly contains a disproportionably low 2–4 mm particle size fraction. As scouring during flood periods removes fine sediments, the size of the bed is often bimodal, with a dominant gravel mode coarser than 4 mm, and a subordinate sand mode of material matrix material finer than 2 mm (Carling and Reader, 1982; Petts *et al.*, 1989). Matrix content in natural gravel-bed rivers is typically between 10 and 28% (Carling and Reader, 1981). Particle size analysis of 157 gravel samples (< 63 mm) collected from Plynlimon streams during 1996 and 1997, by both freeze coring (n=132) and conventional grab sampling (n= 25), revealed an average matrix content of 11%.

Survival rates of salmonid eggs and newly hatched alevins within the spawning bed gravel are reduced as the proportion of fine matrix material increases in relation to the gravel fraction (Platts *et al.*, 1989; Scrivener and Brownlee, 1989; Forestry Authority, 1993). Primarily, this can be related to the reduction in intragravel permeability and dissolved oxygen supply. Further reductions in salmonid spawning success associated with sediment deposition can be caused by reduced spawning gravel porosity, area and stability, and impacts upon post emergence alevin health and predation susceptibility.

Fluvial particulate inputs during natural flood events and high erosion potential may not result in significant gravel sedimentation, as under such conditions input material is entrained and transported from upland spawning areas. As salmonid spawning gravels tend to be located in upland reaches, subsequent deposition in lowland areas may not necessarily affect reproductive success. Impacts of sediment deposition are most significant when fluvial particulate inputs correspond to periods of low discharge and therefore limited transport potential, when fine material can easily infiltrate the gravel. Consequently, even relatively small particulate inputs during low flow conditions can result in significant sedimentation impacts. This can be caused by enhanced soil erosion by land-use practices associated with commercial forestry which do not always correspond with periods of high flow (Leeks, 1992).

Intragravel Permeability and Dissolved Oxygen Supply

Salmonid egg and alevin survival depends upon the relative values of oxygen consumption and delivery. Delivery of intragravel dissolved oxygen (DO) is controlled by its concentration in the *surface* river-water and the intragravel flow rate. The latter depends on gravel permeability, which decreases as the proportion of fine matrix material increases. Reduced permeability, and therefore intragravel flow, associated with sediment deposition can lower DO availability below the critical survival thresholds of around 3–5 mg l^{-1}, at field temperatures of about 5°C, for salmonid egg and alevin survival (Wightman, 1987; Stott, 1989; Naismith *et al.*, 1996). Low and high gravel permeability has therefore been attributed to low (Lacroix, 1985) and high (McNeil and Ahnell, 1964) salmonid spawning success respectively.

To ensure sufficient intragravel DO for successful salmonid reproduction, MAFF (1991) reported that spawning gravel permeability should exceed 1 m hr^{-1}, corresponding to a maximum fines content between 12 and 15%. Calculations of permeability have therefore been used to assess gravel suitability for salmonid spawning. This was undertaken by Moring (1982), who reported that, due to fluvial sediment inputs associated with forest harvesting in Oregon U.S.A., the average gravel permeabilities in three tributaries of the Alsea River significantly decreased.

In addition to impacts associated with DO supply, reduced gravel permeability may inhibit the removal of metabolic waste products (Moring, 1982; Scrivener and Brownlee, 1989), and can limit the supply of drifting food to newly hatched alevins before their emergence to the main river.

Gravel Porosity

Gravel porosity is a measure of intragravel pore spaces and their connection with the main river environment, and also decreases as the proportion of fine matrix material increases. Many authors have attributed the entrapment of newly hatched alevins to reduced porosity, and therefore the prevention of successful emergence (Megahan *et al.*, 1980; Olsson and Persson, 1986; Petts, 1988; Ringler and Hall, 1988; Scrivener and Brownlee, 1989). Although Crisp (1993) reported that alevin emergence through several centimetres of sand above the spawning gravel had little effect on survival, this was under experimental conditions with clean sand. It is likely that material deposited under natural conditions would include finer particles and organics which may increase mortality due to entrapment and oxygen depletion respectively (Beaumont, 1997).

Spawning Gravel Area and Stability

Spawning fish will avoid turbid water and gravels affected by sedimentation. Consequent limitation of the potential spawning area may result in inefficient spawning at suitable sites due to excessive redd construction. Increased density of spawning fish may also increase their vulnerability to predation and overfishing (Olsson and Persson, 1986; Maitland *et al.*, 1990).

Reduced channel depth associated with sediment deposition can create a physical barrier to migration, and can even result in sub-surface summer flows (Forestry Authority, 1993). However, as salmonids migrate during the autumn/winter seasons, corresponding to periods of high flow, such an impact on migration is unlikely, but will obviously affect the standing crop of juveniles (Wightman, 1997).

Plynlimon research has identified bed load yields significantly higher from forested than from grassland catchments (Leeks, 1992; Leeks and Marks, 1997). Inputs of coarse sediment can encourage gravel erosion (Forestry Authority, 1993). This may result in egg mortality by either the direct removal of salmonid redds, or increased egg susceptibility to wash out due to the shallowing of redd depth associated with the erosion of overlying material. Tripp and Poulin (1986) investigated the impacts of gravel scouring, associated with fluvial sediment inputs from forest harvesting, on salmonid spawning habitats within streams on the Queen Charlotte Islands, Canada. Within logged reaches, estimated egg losses were 66–86% for chum salmon (*Oncorhynchus keta*) and 45–70% for coho salmon (*Oncorhynchus kisutch*). Losses of only 2–14% and 0–4%, for chum and coho salmon respectively, were recorded in stable reaches.

Gravel deposition associated with inputs of coarse sediment may increase the potential spawning area. Recently deposited gravel will, however, tend to have a lower critical erosion threshold, thereby reducing its resistance to mobilisation during flood periods. This can result in spawning bed instability and, consequently increased mortality of salmonid eggs and alevins (McNeil, 1966).

Post Emergence Alevin Health and Predation Susceptibility

As the homogenous particle size in simulated redds decreased from 32 to 1.5 mm, premature emergence and an extension of the total emergence period of brown trout (*Salmo trutta*) alevins was reported by Olsson and Persson (1986). It was suggested that this response may be triggered by gravel fining associated with sediment deposition, and represent an adjustment of trout to increase survival in streams with unstable spawning gravels. However, premature alevins are poor swimmers due to their small size and large yolk reserve, and the predator satiation possibly associated with synchronous emergence may not be apparent if emergence period is extended. Predation susceptibility could therefore be increased with a consequent reduction in post emergence survival. It should, however, be recognised that, given the wide range of particle sizes in natural river gravels, as indicated by studies at Plynlimon, it is unclear how fine material deposition within a typical gravel of mixed size composition would affect alevin emergence patterns.

IMPACTS OF GRAVEL COMPOSITION UPON SUCCESSFUL SALMONID REPRODUCTION

Fines infiltration is the main cause of reduced spawning gravel quality and therefore salmonid reproduction success associated with fluvial particulate inputs. Although not identified by recent studies at Plynlimon, bed material fining within upland gravel bed rivers has been associated with forestry land use (Leeks, 1992; Stott, 1997). The most appropriate gravel characteristic which can be used to measure this is particle size. However, particle chemistry and shape, and variation in response and behaviour between fish species are also important.

Particle Size

Optimum survival of salmonid eggs and alevins will occur within a specific size range of bed material. Megahan *et al.* (1980) reported 6.7–101.6 mm as the ideal spawning gravel particle size range for North American salmonids, outside which reproduction success is significantly reduced. Similar relationships exist for British species. Crisp and Carling (1989) demonstrated that, despite the availability of a wide variety of gravel sizes, chosen salmonid redds in north east England and south west Wales usually had a median grain size of 20–30 mm (coarse gravel), indicating selection by the fish.

Authors agree that a high percentage of fines in spawning gravels will be detrimental to fish populations (Fraser,1972; Platts and Megahan, 1975; Tappel and Bjornn, 1983). As sediment deposition commonly results in gravel fining, variation in the proportion of material below a specific size threshold can be appropriate for impact assessment associated with fluvial particulate inputs.

Petts (1988) stated that the most significant grain-size measurement relating to reductions in salmonid egg and fry survival is variably defined as the proportion of inorganic sediment finer than a critical size of between 9.5 mm and 0.84 mm. North American authorities have used the proportion finer than 1 mm to assess spawning gravel quality (Cordone and Kelley, 1961; Adams and Beschta, 1980). Some studies have attributed reduced reproduction success of specific salmonid species to the proportion of spawning bed material finer than a critical size threshold of 6.35 mm for chinook salmon *(Oncorhynchus tshawytscha)* (Bjornn, 1973), 0.83 mm (Hall and Lantz, 1969) and 3.33 mm (Ringler and Hall, 1988) for coho salmon, 0.83 mm for pink salmon (McNeil and Ahnell, 1964) and 0.84 mm for Pacific salmon (Bradley and Reiser, 1991). Similar relationships have been reported for British species. Olsson and Persson (1986) correlated reduced reproduction success of brown trout with the proportion of spawning bed material finer than 18 mm.

Upper limits of spawning gravel material below a critical size threshold have been determined for successful salmonid reproduction. Some studies have suggested low salmonid reproduction success within spawning gravels containing >20% of fine material (<2 mm) (Petersen, 1978; Wightman, 1987; Naismith *et al.* 1996). Similarly, Ottaway *et al.* (1981) reported that good spawning gravels in the River Tees contained <25% of fine material. The U.K. Forests and Water Guidelines (Forestry Authority, 1993) state that ideal spawning gravels contain less than 15% by weight of material finer than 1 mm.

A recent study of gravel composition at five sites in the headwaters of the River Severn at Plynlimon, involving sample collection by both freeze coring and conventional grab methods, revealed a maximum fines (<2 mm) content of just over 17%. In light of the above thresholds, fines concentration at these sites do not pose a serious threat to successful salmonid spawning.

Particle Organic Content

As oxygen is utilised during its decomposition, deposition of fine organic debris will exacerbate any impacts of dissolved oxygen deficiency associated with reduced spawning gravel permeability. This is likely to be particularly significant in forested catchments, within which fluvial particulate loads may consist of up to 20% organic material (Maitland *et al.*, 1990), particularly during harvesting (Ringler and Hall, 1988).

Particle Shape

Particle shape can influence sedimentation rates and gravel permeability and winnowing. Scrivener and Brownlee (1989) reported that round gravels accumulate more fine sediment than angular material during periods of low flow, but this relationship is reversed as flow rates increase. Once fines have intruded into the streambed, permeability and cleaning potential is thought to increase with gravel roundness (McNeil and Ahnell, 1964).

Variation in Fish Response and Behaviour Associated with Species and Size

The effect of gravel sedimentation on salmonid reproduction will also depend on a number of biological factors. Sedimentation impacts within specific horizons will depend on redd depth. Susceptibility to short-term sedimentation impacts will depend on the timing of spawning, and therefore the development of eggs and newly hatched alevins.

To assess the potential impacts of sediment deposition accurately, it is important to identify the habitat importance of the horizons affected. Studies of the most common salmonid species found in British gravel bed rivers, brown trout, sea trout (*Salmo trutta*) and Atlantic salmon, report increasing redd depth with fish size (Ottaway *et al.*, 1981; Elliott, 1984). For these species, the regression lines of Crisp and Carling (1989) indicate egg burial depths ranging from 8 to 24 cm as female fish length increases from 20 to 80 cm.

Due to size variation, a very rough approximation is that brown trout, sea trout and Atlantic salmon construct their redds within 0–10, 10–20 and 20–30 cm depth zones respectively within the spawning gravel (Beaumont, 1996). Consequently, the eggs of migratory fish may be more protected from wash-out, but increasingly vulnerable to sedimentation which is often more significant within deeper horizons (Crisp and Carling, 1989).

Void spaces in surface gravel layers must be sufficient to allow hatched alevins to escape (Scrivener and Brownlee, 1989). As salmon fry are generally larger than those of trout, limited porosity reduction may restrict the movement of only salmon alevins. Thus sedimentation impacts in upper gravel horizons, where only brown trout redds are constructed, may indirectly affect the reproductive success of fish that bury their eggs deeper.

The significance of short-term spawning gravel fining will depend on both the existence of eggs or alevins and their stage of development. In British rivers, the critical period when eggs and alevins are living in the spawning gravels, and are therefore vulnerable to the effects of siltation, is normally from October to March (Turnpenny and Williams, 1980; Milner *et al.*, 1985). As intragravel development rate depends mainly on temperature, this can extend to May or even June in some northern and / or upland streams (Wightman, 1997).

Although oxygen demand is highest around hatching time (Hayes *et al.*, 1951), the relationship between salmonid egg and embryo development and susceptibility to impacts associated with spawning gravel fining is unclear. Both reduced (Stuart, 1953; Cordone and Kelley, 1961; Bradley and Reiser, 1991) and increased (Naismith *et al.*, 1996) susceptibility with stage of development have been reported.

IMPACTS OF FLUVIAL SEDIMENT INPUTS ON POST EMERGENCE SURVIVAL

After emergence from the spawning gravel, the most significant impact of fluvial sediment inputs on salmonid fish is the influence of suspended particulates. This can be divided into the effect of suspended material on gill functions, and the lesser effect of reduced visibility associated with turbidity on feeding and social organisation.

Gill Functions

Suspended sediment may cause gill irritation and damage by congestion and mechanical abrasion (Cordone and Kelley, 1961; Alabaster, 1972). Berg and Northcote (1985) observed gill irritation in juvenile coho salmon subjected to sediment associated turbidity of just 20 nephelometric turbidity units (NTU). In the headwaters of the River Severn at Plynlimon, an approximate 1:1 relationship exists between sediment concentration in mg l^{-1} and turbidity in NTU. Such impacts are therefore likely in similar upland forested catchments, where suspended sediment concentrations exceeding 20 mg l^{-1} commonly occur during hydrological events (Leeks and Marks, 1997).

Suspended sediment can also increase the susceptibility of fish to disease. Mucus secretion from irritated gill tissues provides a focus for the growth of bacteria and fungus (Berg and Northcote, 1985) and abrasive damage can provide a route of entry for pathogens (Kelly, 1994).

Reduced Visibility Associated with Turbidity

a. Feeding

Increased turbidity associated with suspended sediment can result in sight impairment, reducing the success of sight feeding by predatory fish such as salmonids (Hynes, 1973; Wilzbach *et al.*, 1986). As food is often scarce in the headwater streams which drain upland forested catchments, an increase in either the magnitude, frequency or duration of turbidity events could therefore affect fish health.

Although salmon have been observed to cease feeding during spate conditions and associated high turbidity (Kelly, 1994), it cannot be established whether this is due to an inability to feed by visual stimuli, or an attempt to seek shelter during the flood period. Detailed investigations have, however, been undertaken to quantify the reduction in feeding efficiency specifically associated with turbidity. Berg and Northcote (1985) reported that coho salmon subjected to a suspended sediment pulse, and associated turbidity increase from 0 to 30 NTU, showed significant reductions in reactive distance, prey capture success and the percentage of prey ingested. Similarly, Barrett *et al.* (1992) identified that the average reactive distances of rainbow trout (*Oncorhynchus mykiss*) in 15 and 30 NTU treatments were only 80% and 45% respectively, of those observed at ambient turbidities (4–6 NTU).

Significant reductions in feeding efficiency have been associated with specific concentrations of suspended sediment. Although it may also reflect additional stress imposed by the unfamiliar environment, a suspended sediment concentration of just 3–4 mg l^{-1} stops salmonids feeding in an artificial site (Kelly, 1994). Bachmann (1958), in Cordone and Kelley (1961), investigated the effect of suspended sediment on rainbow trout feeding within a natural river. While fish within a control section fed actively, those subjected to an artificially created silt turbidity of 35 mg l^{-1} for two hours, although showing no distress or mortality, ceased feeding and moved to cover.

b. Organisation

As the social organisation of many fish populations, especially salmonids, is influenced strongly by visual contact, territoriality is affected by the reduced visibility associated with turbidity. Berg and Northcote (1985) reported that when a coho salmon population was isolated visually at 30 NTU, dominance hierarchy and territoriality was disrupted, and reformed when turbidity decreased to 20 NTU. As territoriality provides greater feeding opportunity and reduces energy expenditures, predation and the risk of movement to less favourable habitats, this could have adverse impacts upon fish populations.

Fish use visual contact with the bed to maintain position in flowing water. Consequently, movement to less favourable holding positions may also reduce feeding success during periods of high turbidity, when fish have been observed to move to the bottom to make visual or even tactile contact (Berg and Northcote, 1985).

c. Migration

During migration, in addition to increased discharge and changes in water chemistry, high turbidity in estuarine waters has been linked to the successful entry of salmonids to a river system (Wightman, 1997). Within the river, however, further migration may be barred by excessive turbidity (Forestry Authority, 1993).

d. Conclusion

Continuous turbidity monitoring in the headwaters of the River Severn has identified that events of suspended sediment concentration which could affect visibility normally persist no longer than several hours (Marks and Leeks, 1997). The limited duration of these events implies that reduced visibility associated with turbidity is unlikely to represent a serious impact of fluvial sediment inputs to upland gravel bed rivers.

Threshold Concentrations of Suspended Sediment

It is evident that suspended particulates can have a number of adverse affects on fish. However, physical variation between sediment properties and transport dynamics, intra- and inter-species biological differences, and combined impacts with chemical pollutants prevents accurate assessment of the potential impacts associated with specific concentrations.

Impacts upon gill functions may depend more on the physical properties of suspended particles than concentration. Consequently, threshold levels, above which gill functions will be affected, cannot be defined. For a specific suspended sediment concentration, gill damage is likely to be more significant for finer particle sizes which can cause significant gill abrasion by passing or lodging between lamellae (Kelly, 1994). Furthermore, particles which can pass through the primary lamellae of the gill, which is resistant to such damage, can then affect the more delicate secondary lamellae. Particle shape, texture and mineralogy will also govern the effect on gill function. Hard angular solids cause more surface abrasion than soft, rounded or organic particles. The latter, however, are more likely to adhere to fish gills and cause damage by clogging (Kelly, 1994).

As particle heterogeneity introduces considerable scatter in the positive relationship between suspended sediment concentration and turbidity, turbidity impacts cannot be related to specific suspended sediment concentrations. Similar to impacts upon gill function, turbidity increases will generally be more significant for finer particle sizes, but other properties such as mineralogy and shape introduce further variation (Gippel, 1989).

The dynamics of suspended sediment transport will also affect its impact on fish. For an equivalent concentration or turbidity, the gradual increase and decrease common during natural high flow events may result in less severe impacts than sudden pulses unrelated to flow, caused by the direct supply of material to the river channel, which can occur during commercial forestry operations such as drain clearance. Berg and Northcote (1985) identified that the alarm reaction exhibited by salmonids, subjected to a sudden increase of suspended sediment was not apparent when an equivalent concentration was attained gradually over several hours. It was reported that this may cause downstream displacement away from the sediment source, potentially into less favourable habitats. Such impacts are, however, unlikely in upland forested catchments similar to the headwaters of the River Severn at Plynlimon, where most events of high suspended sediment concentration, above background levels of 0–10 mg l^{-1}, are associated with periods of high flow and are therefore attained gradually over a number of hours in association with the flood hydrograph (Leeks and Marks, 1997).

Impacts on gill functions can also vary with the transport pattern of suspended sediment. While acute exposure can lead to immediate mechanical damage, chronic exposure can also result in the fusion of gill lamellae (Wightman, 1997). In upland forested catchments similar to the headwaters of the River Severn, hydrological events rarely persist for more than several hours duration, and even during longer flood periods, or repeated individual hydrological events, hysteresis effects reduce the suspended sediment concentration for an equivalent discharge (Leeks and Marks, 1997). Consequently, chronic exposure to high suspended sediment concentrations is unlikely.

Impacts of suspended sediment which would not pose a serious risk to fish health in isolation may result in fish mortality where water quality is affected by chemical pollutants (Herbert and Merkens 1961; Alabaster, 1972; Maitland *et al.*, 1990). For example, gill damage by toxic chemicals may affect mucus secretion which enables healthy fish to survive the impacts of gill clogging, thereby resulting in fish mortality during conditions of suspended sediment transport which normally pose no serious health risk (Cordone and Kelley, 1961; Berg and Northcote, 1985).

Effects of physical sediment pollution may be exacerbated by impacts associated with the hydrochemistry of upland forested watercourses (Neal *et al.*, 1997). For example, both dissolved inorganic aluminium (Dobbs *et al.*, 1989; Reader and Dempsey, 1989; Wood, 1989) and suspended particulates can affect the respiration of salmonids. Within natural systems affected by fluvial particulate inputs, it may be difficult to isolate the specific impact of suspended particulates from the synergistic stresses induced by other pollutants.

Despite the confounding physical, chemical and biological parameters which affect the relationship between suspended sediment concentration and impacts upon fish health, attempts have been made to define a suspended sediment concentration above which damage can occur and below which there is no adverse affect. Alabaster and Lloyd (1980) stated that any increase in the normally prevailing concentration of suspended material may cause some decline in the status and value of a freshwater fishery. They concluded that, while suspended solids concentrations below 25 mg l^{-1} would probably have no harmful effect, waters containing concentrations of over 80 mg l^{-1} were unlikely to support good freshwater fisheries. Similarly, Hynes (1973) quoted 80 mg l^{-1} as the upper level of suspended sediment tolerable by biota in running water; serious fishery damage may be associated with chronic exposure to concentrations exceeding this threshold. Suspended sediment concentrations in the headwaters of the River Severn at Plynlimon are therefore unlikely to pose a serious threat to salmonids as concentrations exceeding 80 mg l^{-1} are both infrequent and of limited duration.

Impacts of Fluvial Sediment Inputs Upon Invertebrates

Whereas impacts upon fish can be indirect and complex, aquatic invertebrate populations respond more directly to the influence of fluvial particulate inputs. In an investigation into the value of biomonitors of stream quality in agricultural areas, especially as to the relative merits of using fish or invertebrates, Berkman *et al.* (1986) found that invertebrates were more sensitive than fish to habitat quality in sediment-impacted streams.

EFFECTS OF SEDIMENT DEPOSITION UPON INVERTEBRATES

Similar to its suitability for salmonid spawning, particle size will affect habitat quality of bed material for benthic invertebrates. Although the optimum particle size will vary for different species, coarse gravels are likely to be the most productive. These provide a stable habitat with high permeability to ensure the supply and removal of metabolites, and high porosity to provide suitable spaces and connectivity.

Detrimental impacts upon benthic invertebrates have been associated with the fining of bed material (Herbert and Merkens, 1961; Petts, 1987). Even a relatively thin sediment deposit can have a marked effect on stream invertebrates, eliminating certain species such as mayflies and stoneflies and encouraging burrowing worms and midge larvae (Nuttall, 1972). As the latter are less available to predators than the original organisms, this may have significant knock on effects to animals higher in the food chain (Maitland *et al.*, 1990). Investigations have attributed reductions in invertebrate populations to fluvial sediment inputs specifically associated with commercial forestry practice, particularly harvesting operations (Wustenberg, 1954; Tebo, 1955; 1957; 1967; Bachmann, 1958).

EFFECTS OF SUSPENDED SEDIMENT UPON INVERTEBRATES

Adverse impacts of suspended sediment on invertebrates are similar to those reported for fish. This includes impacts upon gill functions by mechanical abrasion, congestion and mucus secretion (Haile, 1983), and reduced sight feeding success associated with turbidity.

Impacts of Fluvial Sediment Inputs on Plants

Plants and algae cycle inorganic nutrients, and through photosynthesis play an essential role in stream aeration and natural purification (Cordone and Kelley, 1961). As they represent an important primary production component of ecological food chains, impacts upon these organisms can significantly affect the entire community within aquatic ecosystems.

EFFECTS OF SEDIMENT DEPOSITION ON PLANTS

Fining of gravel bed material will reduce the surface area available for colonisation by aquatic flora (Cordone and Kelley, 1961). Although not identified by recent studies at Plynlimon, bed material fining within upland gravel bed rivers has been associated with forestry land use (Leeks, 1992; Stott, 1997). In extreme cases, sediment deposition may result in the smothering of benthic plants and algae (Cordone and Kelley, 1961), and deposited fine material may be easily erodible and therefore unsuitable for subsequent colonisation (Maitland *et al.*, 1990). Such impacts are, however, unlikely to be of high significance. As limited stability of bed material in upland river channels constrains plant colonisation or growth, low rates of primary production are likely to be characteristic in this habitat.

EFFECTS OF SUSPENDED SEDIMENT ON PLANTS

Increased turbidity will reduce light penetration through the water column, and can therefore be responsible for limiting the growth of chlorophyllous organisms. Suspended sediment can also destroy algae and plants by abrasive action (Cordone and Kelley, 1961). As Plynlimon data show that events of high turbidity associated with suspended sediment concentrations above background levels rarely persist for more than several hours, this is unlikely to be a serious problem in similar upland forested catchments.

Conclusion

Fluvial sediment inputs from forestry could potentially result in both sediment deposition and transport which may affect fish, invertebrates and plants within upland gravel-bed rivers draining forested catchments.

Impacts of sediment deposition can be separated into the fining of existing bed material, and deposition of additional overlying sediment. Decreased bed permeability and porosity, associated with fining, will reduce the supply and removal of metabolites, and habitat availability and connectivity within this environment respectively. Deposition of additional overlying material can smother organisms living on or within the bed. This can also result in channel depth reduction which, in extreme cases, may bar migration and result in subsurface summer flows. Furthermore, as deposited sediment is commonly less stable than the original material, it can also result in enhanced bed erosion.

As river gravels represent an important habitat for salmonid eggs and newly hatched alevins, sediment deposition can reduce salmonid reproductive success. Although commonly measured by the proportion of bed material below a critical size threshold, the significance of such impacts can also vary with particle composition and shape, and the habitat significance of the affected horizons. For short-term sedimentation, the spawning pattern of adult fish can represent a further control as it governs embryo / alevin development and therefore their susceptibility to such impacts.

Impacts of suspended sediment transport can be separated into those caused by physical contact with particulate material and those associated with turbidity. Suspended sediment can affect fish, invertebrates and plants by physical contact. The gills of aquatic animals are particularly susceptible to suspended particulates, which can abrade and clog these delicate structures. In addition to the prevention of normal gill function, this can also increase disease susceptibility. Increased turbidity will reduce light penetration within the water column, and therefore the photosynthetic activity of chlorophyllous organisms. Sight impairment by the reduced visibility associated with turbidity can affect the feeding, organisation and migration of aquatic animals. The confounding influence of variation between particle properties, transport dynamics and synergistic interactions with other contaminants prevents the association of suspended sediment impacts with specific concentrations.

Natural sediment inputs during periods of high rainfall and flow result in less severe ecological impacts than those which occur during lower flow conditions. As fluvial sediment inputs associated with land-use practices such as forestry are not entirely dependant upon rainfall and flow conditions, they can result in more severe impacts. Whereas suspended sediment concentration and turbidity increases gradually during normal flow events, particulate inputs associated with forestry can result in more immediate impacts. This may result in additional stress which would not have been apparent if an equivalent level of turbidity was attained gradually. Sediment inputs during low flow will also result in much higher sedimentation impacts than would occur during higher flow conditions. Even limited particulate inputs will result in significant sedimentation impacts and potential ecological damage when corresponding with low flow conditions. This is often associated with the direct supply of material to the river channel, which can occur during commercial forestry operations such as drain clearance. Steps have therefore been taken by forest operators to reduce these problems in the form of the Forests and Water Guidelines (Forestry Authority, 1993).

Numerous studies report increased fluvial sediment outputs associated with forestry, often associated with significant ecological impacts. Sediment studies at Plynlimon, however, indicate a limited potential impact to the ecology of similar upland gravel bed rivers. A better integrated understanding of both the particulate outputs associated with forestry, and its impacts, would aid assessment of the potential ecological impacts of fluvial particulate inputs associated with British upland forestry. Integration of geomorphological and biological research is therefore essential for future practical forest management.

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